

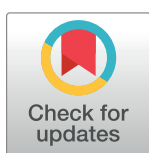
RESEARCH ARTICLE

Investigation of the effectiveness of CFRP strengthening of concrete made with recycled waste PET fine plastic aggregate

Shaker Qaidi^{1*}, Yaman S. S. Al-Kamaki¹, Riadh Al-Mahaidi², Ahmed S. Mohammed³, Hemn Unis Ahmed³, Osama Zaid⁴, Fadi Althoei⁵, Jawad Ahmad⁶, Haytham F. Isleem⁷, Ian Bennetts²

1 Civil Engineering Department, University of Duhok, Duhok, Kurdistan Region, Iraq, **2** Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, Australia, **3** Civil Engineering Department, College of Engineering, University of Sulaimani, Sulaimaniyah, KR, Iraq, **4** Department of Structure Engineering, Military College of Engineering (MCE), National University of Sciences and Technology (NUST), Islamabad, Pakistan, **5** Department of Civil Engineering, College of Engineering, Najran University, Najran, Saudi Arabia, **6** Department of Civil Engineering, Swedish College of Engineering, Wah Cantt, Pakistan, **7** Department of Construction Management, Qujing Normal University, Qujing, Yunnan, China

* shaker.abdal@uod.ac



OPEN ACCESS

Citation: Qaidi S, Al-Kamaki YSS, Al-Mahaidi R, Mohammed AS, Ahmed HU, Zaid O, et al. (2022) Investigation of the effectiveness of CFRP strengthening of concrete made with recycled waste PET fine plastic aggregate. PLoS ONE 17(7): e0269664. <https://doi.org/10.1371/journal.pone.0269664>

Editor: Yasir Nawab, National Textile University, PAKISTAN

Received: April 2, 2022

Accepted: May 26, 2022

Published: July 13, 2022

Peer Review History: PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: <https://doi.org/10.1371/journal.pone.0269664>

Copyright: © 2022 Qaidi et al. This is an open access article distributed under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Data Availability Statement: All relevant data are within the paper.

Abstract

In recent decades, several studies have considered the use of plastic waste as a partial substitute for aggregate in green concrete. Such concrete has been limited to non-structural applications due to its low strength. This raises whether such concrete can be enhanced for use in some structural applications. This paper reports an attempt to develop a structural-grade concrete containing plastic waste aggregate with high proportions of substitution and confined with carbon fiber reinforced polymer (CFRP) fabrics. Experimental research was conducted involving the casting and testing 54 plain and confined concrete cylinders. A concrete mixture was designed in which the fine aggregate was partially replaced by polyethylene terephthalate (PET) waste plastic at ratios of 0%, 25%, and 50%, and with different w/c ratios of 0.40, 0.45, and 0.55. The results show that confinement has a substantial positive effect on the compressive behavior of PET concrete. The enhancement efficiency increases by 8–190%, with higher enhancement levels for higher substitution ratios. Adding one layer of CFRP fabric raises the ultimate strength of samples that have lost compressive strength to a level close to that of unconfined samples not containing PET. This confinement is accompanied by an increase in the slope of the stress-strain curve and greater axial and lateral strain values at failure. For the specimens confined by CFRP fabric, PET aggregate can be used as a partial substitute for sand at a replacement ratio of up to 50% by volume for structural applications. This paper also considers the ability of existing models to predict the strength of confined-PET concrete circular cross-sections by comparing model predictions with experimental results. The strength of confined PET concrete elements can't be accurately predicted by any of the models that are already out there. It's important to come up with a new model for these elements.

Funding: The author(s) received no specific funding for this work.

Competing interests: The authors have declared that no competing interests exist.

Abbreviations: f'_{co} , unwrapped maximum or peak concrete compressive strength; f'_{cc} , wrapped maximum or peak concrete compressive strength; f_l , FRP lateral confining pressure; f_{le} , $f_{l,eff}$, effective lateral confining pressure; $f_{l,a}$, actual confining pressure; $f'_{l,max}$, maximum effective transverse confinement stress; t_{frp} , FRP wrapping thickness; d , inside core diameter of confined concrete section; n , number of FRP layers or plies; E_{frp} , modulus of elasticity of FRP wrapping; ϵ_{ne} , effective strain of FRP at rupture; k_1 , confinement effectiveness coefficient.

1. Introduction

Concrete is one of the world's most popular and widely-used construction materials [1–3]. Every year, around 12 billion tons of concrete are produced worldwide. The ongoing boom in the construction sector has resulted in increased demand for building materials like cement and aggregate. However, aggregate is a non-renewable resource. Continuous quarrying has negative environmental consequences and ultimately depletes aggregate availability. Therefore, measures to reduce the demand for the aggregate need to be developed. On the other hand, PET waste is a form of plastic waste that is growing in lockstep with human waste. PET is one of the major types of plastic and a member of the thermoplastic polyester family [4–7]. The main issue with plastic waste is that it can contain organic and inorganic components, such as food waste; this complicates recycling, and much of this material ends up in landfills. As a result, there is likely to be a lack of landfill sites in the future and increased environmental impact because most wastes are non-biodegradable and stay in the environment for tens of thousands, if not hundreds of years [8–11]. Therefore, valorization of waste plastic as fibers [12, 13] or concrete aggregates [6, 14] has become an opportunity. For example, [15] studied developed the concept of a new preplaced aggregate fiber reinforced concrete (PAFRC) reinforced with waste polypropylene (PP) carpet fibers and investigated its strength properties. Palm oil fuel ash (POFA) was used as a partial cement replacement. Six PAFRC mixes with fibers varying from 0 to 1.25% with a length of 30 mm were made by the gravity method. The study revealed that the carpet fibers have the potential to be used in PAFRC by developing their strength properties.

The principle of adding a substance to another has been used since ancient times to enhance the properties of composite materials. For example, horsehair and straw were added to clay to enhance brick characteristics [16, 17]. Furthermore, concrete has been used with weaker materials to achieve composites with the necessary mechanical properties [18–20]. This includes the potential for turning plastic waste into construction materials by recycling it into green concrete [21, 22]. As a result, the recycling rate will improve, and demand for natural raw material production will decrease. In this way, the environmental pressure on the concrete sector could be reduced, eliminating the need for natural capital and contributing to sustainable production [23, 24]. For this purpose, in recent decades, several studies have considered waste plastic as a substitute aggregate in green concrete (also known as eco-friendly concrete) [25–28]. This approach has been affirmed by many studies which have argued that such recycling is essential for the ecosystem and economic gain [18–20, 29].

The use of PET as a potential alternative to aggregate in concrete will not lead to the concrete being polluted, but some characteristics of the concrete may be affected [22, 30]. In most instances, plastic wastes are used as coarse or fine aggregates in concrete. In previous investigations, specific techniques were used, such as chipping machines or hand cutting, to transform the material into a form suitable for addition to concrete mixes. Generally, different plastic additives have different effects on concrete properties [31, 32]. Therefore, many studies have been carried out over the last three decades to study the effect of plastic waste on concrete [33–48]. However, there are still some negative issues that previous studies have not addressed or solved, such as the decrease in overall mechanical properties when replacing natural aggregates with plastic waste. Most importantly, past studies have indicated that concrete utilizing plastic waste as aggregate is likely to be only applicable to non-structural applications due to its low strength.

In contrast, throughout the last four decades, research has been conducted on the impact of FRP wrapping on the strength and ductility of wrapped concrete under various types of wrapping and loading conditions, with the corresponding development of experimental and

design-oriented models [49–93]. Most investigations have been carried out on cylindrical specimens wrapped in various types of FRP composites, which have no steel reinforcement. Such studies have shown that circular cross-sections have the most effective confinement, whereas square and rectangular sections have the least effective confinement. More confinement can be achieved by wrapping additional layers around the square or rectangular sections when increasing the rounding of corners is difficult. However, a thorough review of the literature found that no study has been done yet to see how well CFRP wrapping concrete made from PET waste works.

Generally, concrete containing PET can be used for non-structural purposes that do not require high compressive strength. However, there seems to have been no attempt to transform PET concrete into concrete capable of being used in structural applications. One way this might be achieved is by wrapping PET concrete with CFRP, and the purpose of this paper is to describe an investigation into this matter. The PET concrete considered in this paper is of a type where PET material has been added to replace a proportion of the aggregate. This work reported in this paper includes an experimental program and an evaluation of whether the design-orientated models reported in the literature for normal and high-strength of concrete are also applicable to confined PET concrete.

2. Significance of the study

The use of renewable materials has recently been observed in many sectors for economic and environmental reasons, in which the utilization of recycled plastic is a significant step toward sustainability. On the other hand, as is well known, FRP reinforcement is used to advance the mechanical properties of the concrete member and structural performance, but little is known about the effect of confining concrete that contains plastic waste. Therefore, the uniqueness of this study is that the behavior of concrete containing PET plastic waste confined by CFRP fabrics has not been investigated yet. This study will attempt to bridge this gap.

3. Experimental program

3.1. Materials

In this test program, ordinary Portland cement (OPC) Type I, with the brand name Tasluja, was used. The chemical properties and physical properties of the OPC are presented in Tables 1 and 2, respectively. Natural sand from the Khabour quarry in Duhok city was used in the concrete mixes. The grading test and physical properties of fine aggregate are presented in Table 3. Furthermore, crushed natural aggregate from the Sejie zone in Duhok city was used to prepare mixes, with the nominal maximum size passing through a 19 mm sieve. The gravel was cleaned and washed with water several times and allowed to dry in the air. Generally, water suitable for drinking is also suitable for use in concrete. In all concrete mixes and for curing of specimens, potable tap water at laboratory temperature without salt or chemicals was used. To improve workability, a high-range water-reducing admixture (superplasticizer) known as Sika® ViscoCrete®-1316 Hi-Tech was added to the mixes. The manufacturer recommends that the dosage should be in the range of 500–1500 gm for 100 kg of cement. In addition, this type of admixture is compatible with ASTM C494 (types D and G) [94]. Table 4 shows the key properties of this superplasticizer.

Furthermore, in this investigation, PET particles were prepared by grinding PET waste bottles (type BC210) [95]. These PET bottles were supplied by the Light Plastic Factory [96]. The PET waste particles were produced in the following steps:

1. Remove the bottle caps.

Table 1. The chemical characteristics of ordinary Portland cement*.

Chemical Requirements		Test Result	Limitation (IOS.) (No. 5/1984) [100]
SO ₃	%	2.24	2.5 if C ₃ A < 3.5
			2.8 if C ₃ A > 3.5
SiO ₂	%	19.11	–
Al ₂ O ₃	%	6.42	–
MgO	%	3.82	< 5.0
Fe ₂ O ₃	%	3.73	–
CaO	%	66.26	–
C ₂ S	%	19.91	–
C ₃ S	%	50.40	–
C ₃ A	%	7.67	–
C ₄ AF	%	10.03	–
Insoluble residue	%	0.96	Not more than 1.5%
Loss on ignition	%	2.2	Not more than 4%
Lime saturation factor	%	0.91	0.66–1.02
Chloride Quantity	%	0.01	–

* This test was carried out by the quality control department at Tasluja cement factory.

<https://doi.org/10.1371/journal.pone.0269664.t001>

- Shred and grind the bottles to a size similar to sand using a plastic granulator machine (SG-600F Model SML). This machine is used for plastic manufacturing by the Light Plastic Factory.
- Sort the particles using sieves, and retain particles that pass through a 4.75 mm sieve. See Fig 1.

After the PET aggregate was prepared, it was evaluated in grading by sieve analysis, as illustrated in Table 5. The physical and mechanical characteristics of the PET material are shown in Table 6 as provided by the Light Plastic Factory [96]. Due to the plastic texture and the plastic particle types, which are often flaky, angular, and irregular particles, the sieve analysis of PET aggregate does not conform to that of natural sand grading, as the fine natural aggregate is typically composed of spherical and granular particles.

Used in this test program were unidirectional CFRP sheets (SikaWrap-300C) [97] with fibers directed along the longitudinal axis. The CFRP sheet characteristics depend on the specifications offered by the supplier, Sika Company, and are shown in Table 7. Epoxy resins are generally utilized to bond CFRP to concrete. The adhesive material Sikadur-330 [98] was used in this test program. Five CFRP coupons with an average dimension of 15 mm × 250 mm and

Table 2. The mechanical and physical characteristics of ordinary Portland cement*.

Physical & Mechanical Requirements	Test Result	Limitation (IOS.) (No. 5/1984) [100]
Initial setting time (minute)	190	≥ 45 min
Final setting time (minute)	240	≤ 600 min
Fineness (Blaine)(cm ² /g)	3470	≥ 2300
Compressive strength (3 d) (MPa)	25	≥ 15 MPa
Compressive strength (7 d) (MPa)	35	≥ 23 MPa

* This test was carried out by the quality control department at Tasluja cement factory.

<https://doi.org/10.1371/journal.pone.0269664.t002>

Table 3. Grading test and physical properties of fine aggregate.

Type of test Grading test	Results (Zone 2)	Limitations (IQS.) (No.45/1984) [101]			
Sieve size (mm)	% Passing	Zone 1	Zone 2	Zone 3	Zone 4
10	100	100	100	100	100
4.75	100	100–90	100–90	100–85	100–95
2.36	80	95–60	100–75	100–85	100–95
1.18	65	70–30	90–55	100–75	100–90
0.6	50	34–15	59–35	79–60	100–80
0.3	19	20–5	30–8	40–12	50–15
0.15	5	10–0	10–0	10–0	15–0
Physical properties					
Fineness Modulus (FM.)	2.81		–		
Specific gravity (SSD)	2.7		–		
Absorption %	1.14		–		
Bulk Density (kg/m ³)	1634		–		

<https://doi.org/10.1371/journal.pone.0269664.t003>

a standard tensile testing machine with a head displacement rate of 2mm/min were prepared and tested as per the ASTM D3039/D3039M standard [99]. The test data on CFRP coupons are presented in Table 7. The epoxy resin adhesive system consists of the main resin portion (Part A, white color) and the hardener (Part B, grey color), blended at a particular volume ratio of 4A:1B for about 10 minutes until the color becomes grey. It is then applied to the concrete surface using a paintbrush. A table called "Table 8" shows the material properties of an epoxy adhesive made by the company called "Sika."

3.2. Preparation and details of samples

In this experimental study, nine concrete mixes were produced containing different volumetric replacements of fine natural aggregate (0%, 25%, and 50%) by PET plastic waste with three different grades: M20, M30, and M40. The mix design was made following the American method ACI 211.1-91-R-02 [104]. A total of 54 cylinders with dimensions of 150 × 300 mm were prepared and tested (3 replacement ratios × 3 W/C ratios × wrapped/unwrapped × 3 repeats = 54). Three test specimens (i.e., three repeats) were considered for each case to ensure the reliability of the test results. These cylinders were divided into nine mixes (3 replacement ratios × 3 W/C ratios), with six cylinders in each mix.

To monitor and standardize the mixing process for all experiments, the mixing for all concretes was carried out in an electric rotary tilting drum mixer of 0.1 m³ capacity by the procedure specified in ASTM C192/C192M [105]. A constant amount of 0.035 m³ of materials was arranged for each mixture. Shovels and scoops were used to deposit the mixed concrete into the moulds. The same methodology was used for the preparation of all mixtures. After the mixing process was finished, the mixed concrete was poured into the iron moulds. The moulds were cleaned before casting, rigidly tightened, and lightly oiled to avoid adhesion to the

Table 4. Specifications of superplasticizer.

Properties	Description
Appearance	Brownish liquid
Specific gravity	1.123 ± 0.01 kg/l
Chloride content	Max. 0.1% Chloride-free
Chemical base	Modified polycarboxylate-based polymer

<https://doi.org/10.1371/journal.pone.0269664.t004>



Fig 1. Sieving of aggregates: (a) coarse; (b) fine; and (c) PET.

<https://doi.org/10.1371/journal.pone.0269664.g001>

concrete. After mixing, the moulds were filled and the concrete compacted by a Mallet hammer according to ASTM C192 [105].

Good quality concrete must be cured. For this reason, 24 hours after concrete casting, all specimens were put in a curing basin at around 25°C. The curing status of the laboratory basin was adopted from ASTM C192 [105]. Fig 2 shows the preparation and curing process of the cylinders. Capping the concrete cylinders is significant to confirm that the load is uniformly distributed on the cylinder's surface during compression testing. For this purpose, before testing, all the concrete cylinders were capped with a 3 mm thick layer of sulfur capping compound. Capping the cylinders followed the procedures prescribed by ASTM C617 [106]. Moreover, tests were performed at the age of 90 days.

3.3. CFRP fabric confinement

Prior to wrapping, the 150 mm × 300 mm cylinders were dried and cleaned, and the concrete strength was 90 days age. At the beginning of the wrapping process, a thin layer of dust covering the specimens was removed with an air compressor. CFRP sheets were then cut into strips of the desired lengths and widths using scissors. Next, the epoxy coating was prepared by mixing the epoxy resin (parts A and B) in a proportion of 4A:1B. After the cylinders were placed upright, they were completely coated with epoxy using a paintbrush. The next stage was to wrap the CFRP sheets carefully around the cylindrical specimens, as shown in Fig 3. The fibers were aligned only in the hoop direction. A 120 to 125 mm overlap was provided to prevent

Table 5. Sieve analysis of PET and fine aggregate.

Sieve size (mm)	% passed of fine aggregate	% passed of waste PET particles
10	100	100
4.75	100	100
2.36	80	35
1.18	65	5
0.6	50	1
0.3	19	0
0.15	5	0

<https://doi.org/10.1371/journal.pone.0269664.t005>

Table 6. Physical and mechanical characteristics of used PET*.

Property	Results
Particle shape	Flaky or flat particles
Water absorption (24 h)	-
Specific gravity	1.39
Bulk density	$850 \pm 10 \text{ kg/m}^3$
Thickness	0.35 mm
Colour	Crystalline white
Tensile strength	79.3 MPa
Approx. melting temperature	230–250°C
Tensile modulus	4.0 GPa

* Provided to us by the Light Plastic Factory [24].

<https://doi.org/10.1371/journal.pone.0269664.t006>

slippage between the CFRP layers. The location of the overlap for all specimens is shown in Fig 3. In addition, the upper and lower ends of the confined cylinders were further strengthened with 50 mm wide strips to prevent premature failure at the ends. Then, after 24 hrs., high-strength sulfur capping was applied to the top end of each specimen. Finally, the confined concrete specimens were rested in the laboratory for seven days.

3.4. Loading procedure

Fiber roving and uneven hardened epoxy needed to be smoothed to fix strain gauges on the cylinders. Sandpaper was used to smooth the fiber surface, which was then cleaned with isopropyl alcohol. Strain gauges were then installed at evenly spaced locations at the mid-height of all specimens. Two strain gauges (model PL-60-11-3LJC-F) were mounted for plain concrete, one horizontally and one vertically, in a T-shape. For the confined cylinders, four strain gauges (model BF350-3AA) were mounted, two horizontally and two vertically, to also form a T-shape. As shown in Fig 4, the load cell and strain gauges were connected to a data logger for data collection during compression. Compressive strength experiments were conducted on the concrete cylinder specimens following ASTM C39 [107]. The tests were performed using a universal test machine (Walter + Bai AG/ Switzerland) with a capacity of 3000 kN and a loading rate of 0.33 MPa/sec.

4. Results and discussions

The key test results at 90 days of curing of all 54 confined and unconfined specimens (cylinders with dimensions $\varnothing 150 \times 300 \text{ mm}$) are given in Table 9. The compressive strengths shown in

Table 7. Properties of CFRP sheet.

Characteristics	Manufacturer data	Test Data
Ultimate tensile strength (MPa)	4000	3553
Ultimate tensile elongation (%)	1.7	1.4
Modulus of carbon fiber (GPa)	230	239
Thickness(mm)	0.167	
Fiber density (g/cm^3)	1.82	
Areal weight (g/m^2)	304 ± 10	
Fiber orientation (°)	0	
Fabric width (mm)	500	

* According to the product data sheet (SikaWrap - 300C) [102].

<https://doi.org/10.1371/journal.pone.0269664.t007>

Table 8. Material characteristics of epoxy adhesive.

Characteristics	Manufacturer data
Modulus of elasticity (MPa (4500
Elongation limit (%)	0.9
Tensile strength (MPa (30
Mixing ratio (by weight)	Part (A) $\frac{1}{4}$ 4: Part (B) $\frac{1}{4}$ 1
Colour (when mixed)	Light grey
Density (kg/l)	1.30 ± 0.1 (A + B mixed) (at + 23°C (

* According to the product data sheet (Sika ViscoCrete Hi-Tech 1316) [103].

<https://doi.org/10.1371/journal.pone.0269664.t008>

the table represent an average of three specimens per mixture, while the axial and lateral strains represent the means of two specimens per mixture.

4.1. Effect of PET on strength reduction

The results shown in Table 9 demonstrate the impact of replacing a natural aggregate with a plastic aggregate. Generally, as the substitution percentage of PET particles increases, the compressive strength decreases. For example, compared to the reference mix, at 25% replacement (90 days), the reduction in strength is 43.46% (w/c of 0.40), 40.96% (w/c of 0.45) and 25.2% (w/c of 0.55). At 50% replacement, the rate of reduction is 76.12% (w/c of 0.40), 76.82% (w/c of 0.45), and 74.41% (w/c of 0.55). This strength reduction can be explained as the result of three factors: (a) the smooth surface and flat shape of the plastic particles; (b) the low adhesive strength between the cement paste and the plastic particles; and (c) the barrier formed by the plastic particles, which prevents cement paste from adhering to the natural aggregate. Therefore, for concrete containing PET aggregates, the interfacial transition zone (ITZ) is weaker than for control concrete, and this decreases the resultant compressive strength. Furthermore,

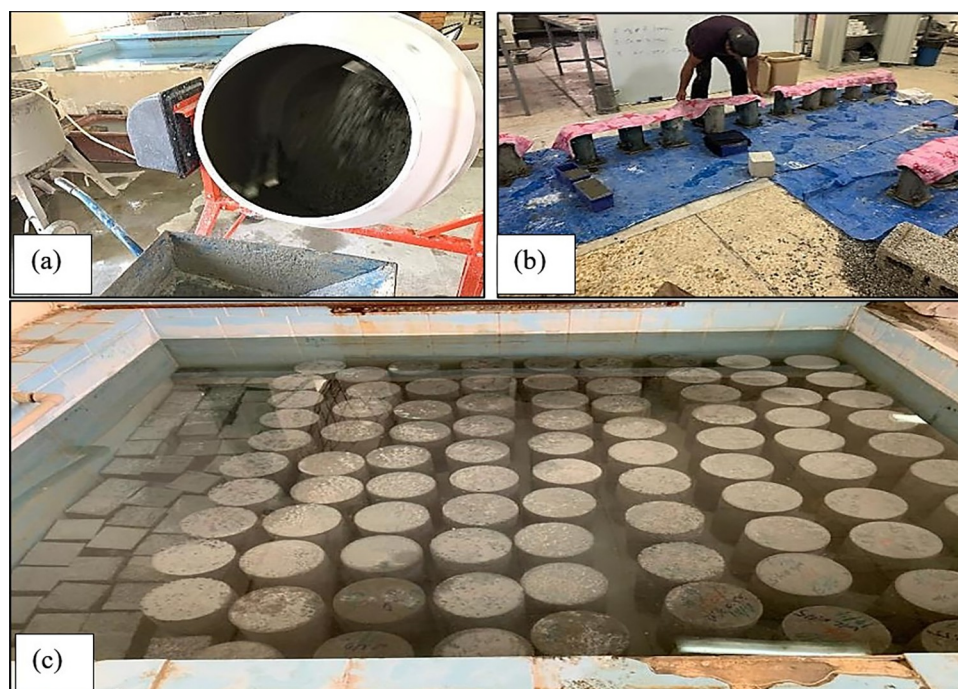


Fig 2. Preparation of specimens: (a) Mixing, (b) Casting and covering, and (c) Curing.

<https://doi.org/10.1371/journal.pone.0269664.g002>

water is not absorbed by the PET, which does not participate in the water-cement reaction, causing poorer bonding and the creation of microscopic channels that can become pores after drying. Several authors have verified these observations [48, 108, 109].

Furthermore, an increase in the w/c ratio corresponds to a decrease in compressive strength, similar to conventional concrete mixtures. It is worth noting that at larger w/c ratios, the aggregate's coated surface is smaller, and as a result of the lower paste volume, the bleeding water content is higher. The excess water, which is primarily found around PET particles that do not participate in the water-cement reaction, causes a weaker bond between the cement paste and the PET particles and the formation of small channels that can form pores after drying, resulting in a reduction in strength.

4.2. Effect of CFRP wrapping on strength enhancement

The experimental results in Table 9 demonstrate the effect of wrapping concrete comprising plastic particles on the compressive strength performance of concrete after 90 days. Irrespective of the substitution ratio of PET and the w/c ratios, one layer of CFRP fabrics with full wrapping causes a substantial improvement of the ultimate compressive strength of PET-concrete cylinders compared to that of unwrapped cylinders. This strength increase can be described by the fact that confinement has served its purpose with PET concrete.

Table 9 and Fig 5 also show that when the w/c ratio is reduced, the enhancement in strength efficiency decreases significantly. In other words, the effect of CFRP wrapping is more significant for samples with low compressive strength than for those with higher strength. The cause of this is that, for lower strength concrete, the concrete core can expand more, and, therefore, higher hoop strains can develop in the CFRP, providing greater confinement prior to rupture. As a result, it is noted that the efficiency of the strength enhancement increases significantly with the increase in the amount of substitution of PET aggregate.

Overall, the strength of cylinders containing PET aggregate and wrapped with one layer of CFRP fabric is significantly enhanced, as shown in Fig 5. This indicates that it is possible to use CFRP fabric to enhance and recover the strength lost due to the substitution of PET for normal aggregate. For instance, with full CFRP wrapping with a replacement rate of 25%, the strength is enhanced (recovered) by 58.9% (89.82%) (for w/c of 0.40), 66.4% (98.26%) (for w/c of 0.45), and 87.8% (140.47%) (for w/c of 0.55). Enhancement (recovery) in strength at a replacement rate of 50% is 133.2% (50.93%) (for w/c of 0.40), 120% (51%) (for w/c of 0.45), and 190.3% (74.27%) (for w/c of 0.55).

4.3. Stress-strain relationships

The stress-strain curves of the nine mixes of cylinders are presented in Fig 6, with the axial strain values being exposed on the left and the lateral strain values on the right. In general, the stress-strain relationships exhibit a linear portion, then as micro-cracking takes place, the shape of the curve becomes increasingly non-linear until it reaches the maximum stress. Fig 6 indicates that increasing the PET aggregate ratio for cylinders confined with CFRP fabrics leads to a significantly increased maximum strain. As the substitution ratio increases, there is a reduction in the initial slope of the axial stress-strain curve and in the value of stress at which the stress-strain curve ceases to be linear. Note that the slope of the non-linear part of the axial stress-strain curve is always positive, due to the confining pressure, which increases rapidly due to the rapid increase in lateral dilation of the concrete.

4.3.1. Failure modes. The failure modes for some of the tested cylinders wrapped in CFRP are shown in Fig 7. It was observed that at low load intensities (initial load), an intermittent sound was heard due to microcracking in the concrete matrix. Several sounds were



Fig 3. CFRP wrapping process: (a) cleaning; (b) cutting of laminate; (c) mixing epoxy resin; (d) coating cylinders; (e) wrapping CFRP laminate; (f) confinement of upper and lower ends; and (g) capping and curing.

<https://doi.org/10.1371/journal.pone.0269664.g003>

detected before the load reached its maximum level, at which such sounds were linked to the rupturing of fibers within the CFRP matrix. Finally, the CFRP sheets broke into rings with a high-intensity acoustic emission. Overall, all wrapped cylinders failed by the sudden rupture of the CFRP jacket close to the mid-height region outside the overlapping zone as the CFRP sheet suffered excessive tension in the hoop direction. It was also found that none of the CFRP-

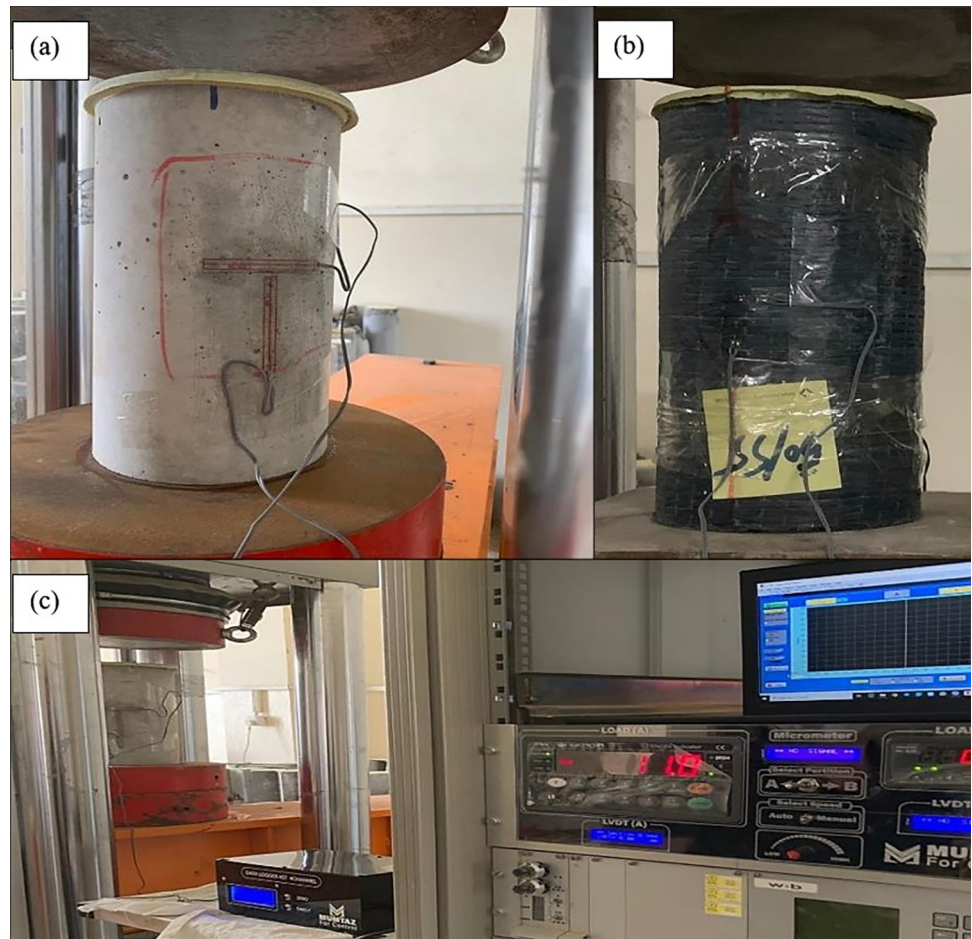


Fig 4. (a) plain cylinder; (b) confined cylinder; (c) compression testing with equipment.

<https://doi.org/10.1371/journal.pone.0269664.g004>

wrapped cylinders failed at the lap location, demonstrating reasonable adhesion and efficient load transfer between the concrete substrate and the CFRP. Two additional observations were made in the case of the CFRP-confined cylinders that contained plastic aggregate, especially at a high percentage of PET (50%), compared to their counterparts without PET: (i) the acoustic emission is less severe; and (ii) the tearing of the CFRP fabric is also less severe. These observations are thought to be due to the existence of plastic particles at the failure starting point, their high flexibility and elongated form, and the possibility that the plastic particles withstand a portion of the stress and act as a bridge between plastic particles parts.

5. Evaluation of existing strength models for prediction of f'_{cc}

5.1. Confinement action (a mechanism) of FRP

The passive confinement mechanism of the FRP shell on a concrete core occurs throughout compression. This action occurs as a consequence of the concrete core's hoop expanding under compression until the FRP ruptures [110–112]. The equivalent hoop strain and stress within the fabric increase as the axial stress increases, exerting restricting pressure on the core. In other words, under compression, the concrete core tends to expand (dilate) laterally, but the FRP fabric opposes this expansion, putting the concrete in a state of triaxial stress, resulting in a substantial

Table 9. Details of test specimens.

Grade / w/c	PET ratio %	Specimen symbols	CFRP layers	Compressive strength (MPa)		**Max. axial strain (%)	**Max. lateral strain (%)
				90 days	Variation of strength (%)		
M40 / 0.40	0	R0WC40*	0	80.13	-	-0.0056	0.0022
			1	86.81	+8.33	-0.011	0.010
	25	R25WC40	0	45.31	-	-0.005	0.0067
			1	71.98	+58.86	-0.010	0.0150
	50	R50WC40	0	19.14	-	-0.0052	0.0082
			1	40.81	+133.25	-0.014	0.0120
M30 / 0.45	0	R0WC45	0	66.83	-	-0.0053	0.0051
			1	82.10	+22.84	-0.0042	0.0140
	25	R25WC45	0	39.46	-	-0.0071	0.0072
			1	65.67	+66.42	-0.017	0.0130
	50	R50WC45	0	15.49	-	-0.0038	0.0094
			1	34.09	120.02	-0.0050	0.0110
M20 / 0.55	0	R0WC55	0	47.73	-	-0.0019	0.0018
			1	69.97	+46.61	-0.0040	0.0109
	25	R25WC55	0	35.70	-	-0.0060	0.0044
			1	67.04	+87.79	-0.0074	0.0139
	50	R50WC55	0	12.21	-	-0.0060	0.0062
			1	35.45	+190.27	-0.01325	0.0132

* R0WC40: The number following the letter R indicates the percentage of PET substitution; the number following the letters WC indicates the w/c ratio.

** Some of the results presented in this column do not correspond to the maximum compressive strength because the foil gauges were broken off) before the sample reached failure. Therefore, if they do not correspond to the maximum strength, the results represent the maximum value in the plotted curves.

<https://doi.org/10.1371/journal.pone.0269664.t009>

gain in strength and ductility compared to unconfined specimens. Fig 8 shows that the pressure from the FRP fabric is mostly even around the outside of the round concrete cross-section.

5.2. Lateral confinement pressure (f_l)

When a compression member is circumferentially wrapped with FRP composites, the fibers in the hoop direction respond against the circumferential concrete dilation. The concrete core is under even confinement pressure (expansion) [62, 113]. This affords a hoop confining pressure (f_l) which is directly affected by the CFRP wrapping and the cross-sectional area of the compression component. It is possible to compute the force equilibrium and radial displacement compatibility criteria between the concrete core and the CFRP fabric [82]. When the CFRP fabric's hoop strain exceeds its rupture strain, the specimen fails quickly in a brittle manner, achieving the CFRP's maximum confinement pressure ($f_{l,max}$). Eq (1) could theoretically be used to calculate the value of $f_{l,max}$ using the average axial strain at failure measured from tensile coupons. Also, such a value could be calculated based on the data provided by the manufacturer in combination with the average axial strain at failure measured from tensile CFRP coupon tests. However, as previously stated, this is likely to overstate $f_{l,max}$.

$$f_{l,max} = \frac{2nE_{frp}\epsilon_h t_{frp}}{d} \quad (1)$$

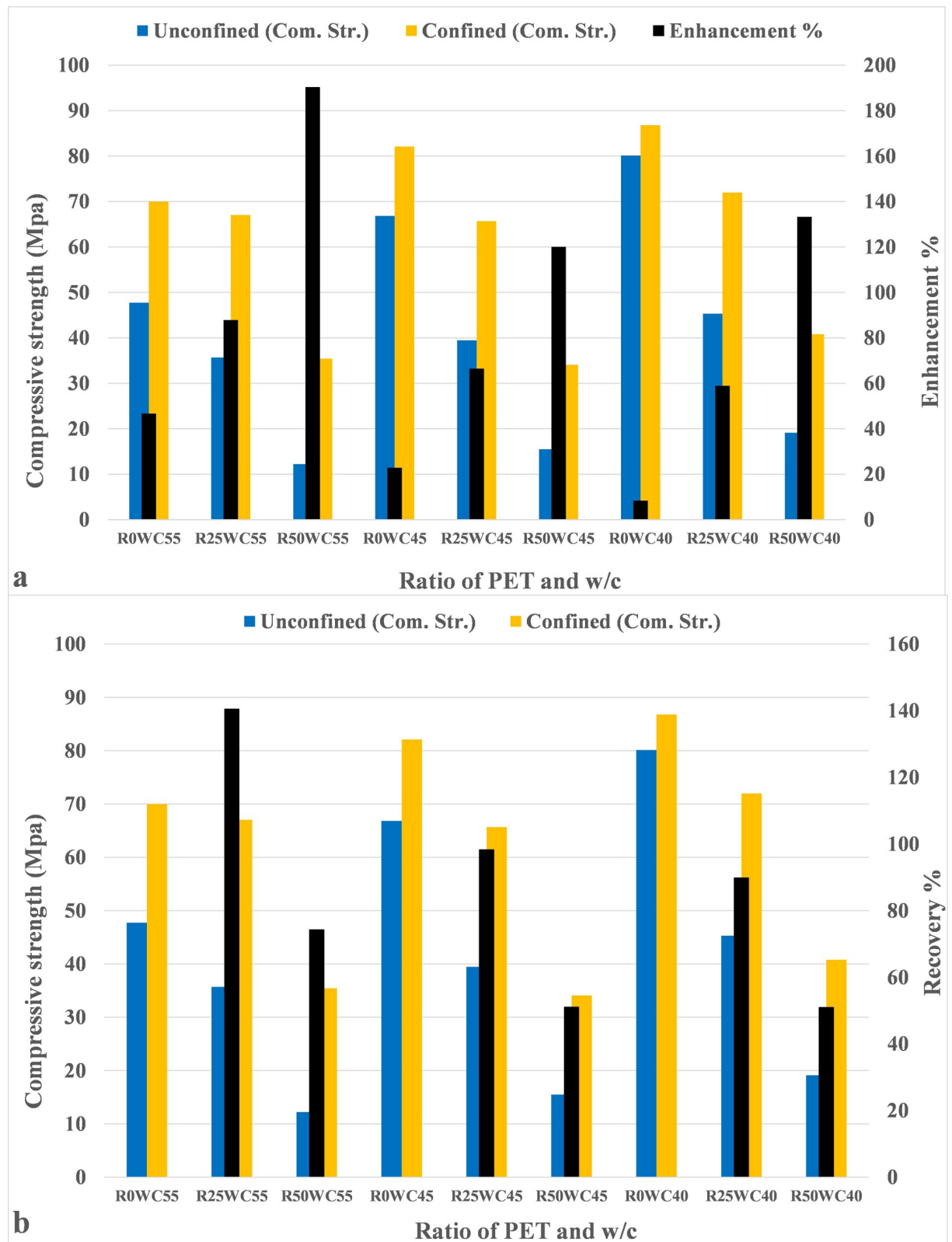


Fig 5. Influence of CFRP wrapping on strength: (a) enhancement; and (b) recovery.

<https://doi.org/10.1371/journal.pone.0269664.g005>

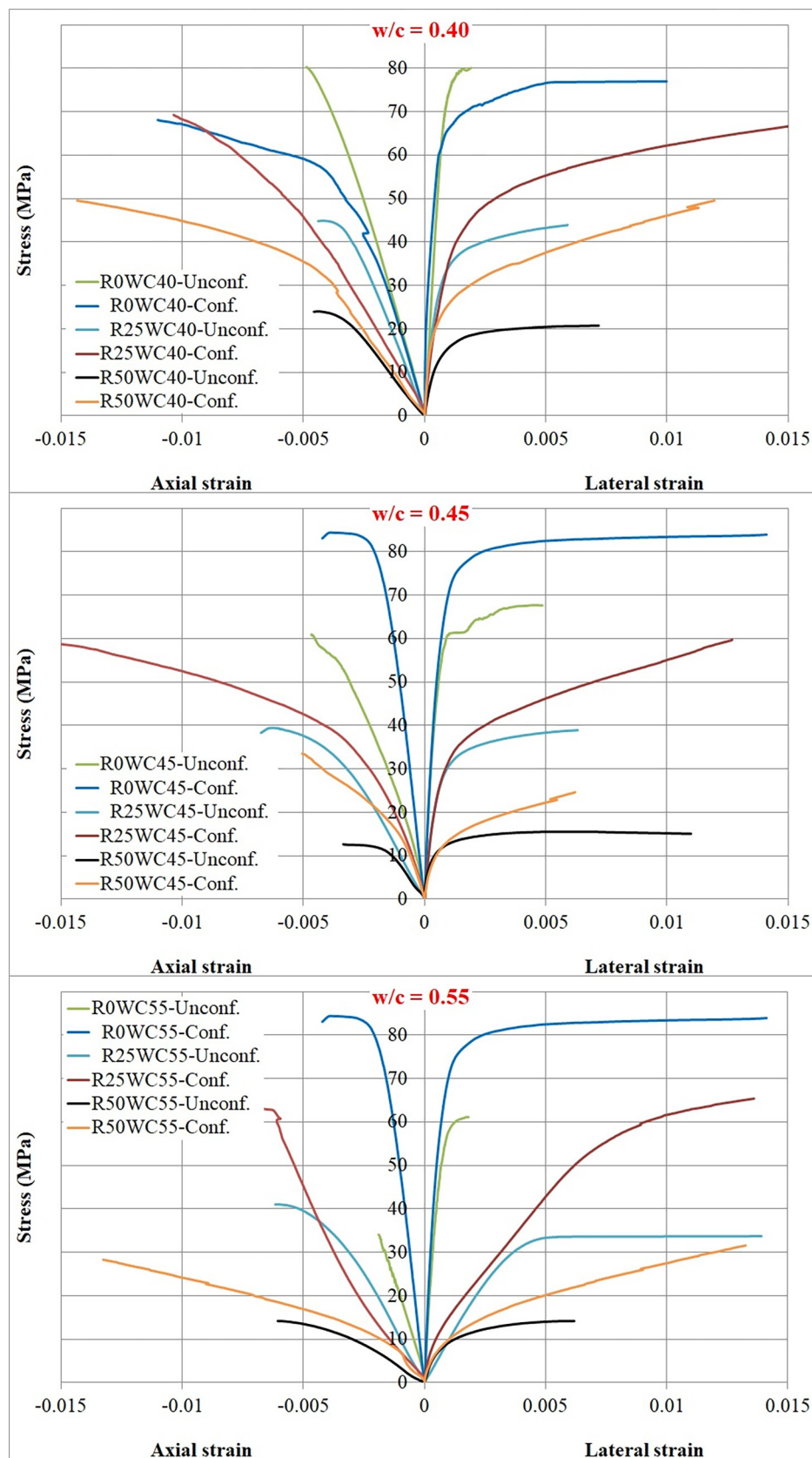


Fig 6. Stress-strain curves of confined and unconfined specimens with different w/c .

<https://doi.org/10.1371/journal.pone.0269664.g006>



Fig 7. Failure modes for some typical cylinders.

<https://doi.org/10.1371/journal.pone.0269664.g007>

5.3. Effective lateral confinement pressure (f_{le})

The CFRP fabric ruptures in the lateral direction as soon as the ultimate compressive strength of concrete samples confined by CFRP wraps is attained. Eq (2) can also be used to compute the effective confining pressure (f_{le}) using the recorded average lateral strain of CFRP-confined concrete from cylinder testing, as shown in Table 9. In this investigation, the average ultimate tensile strain captured at the mid-height of the coupon was 1.4 percent for a single CFRP ply,

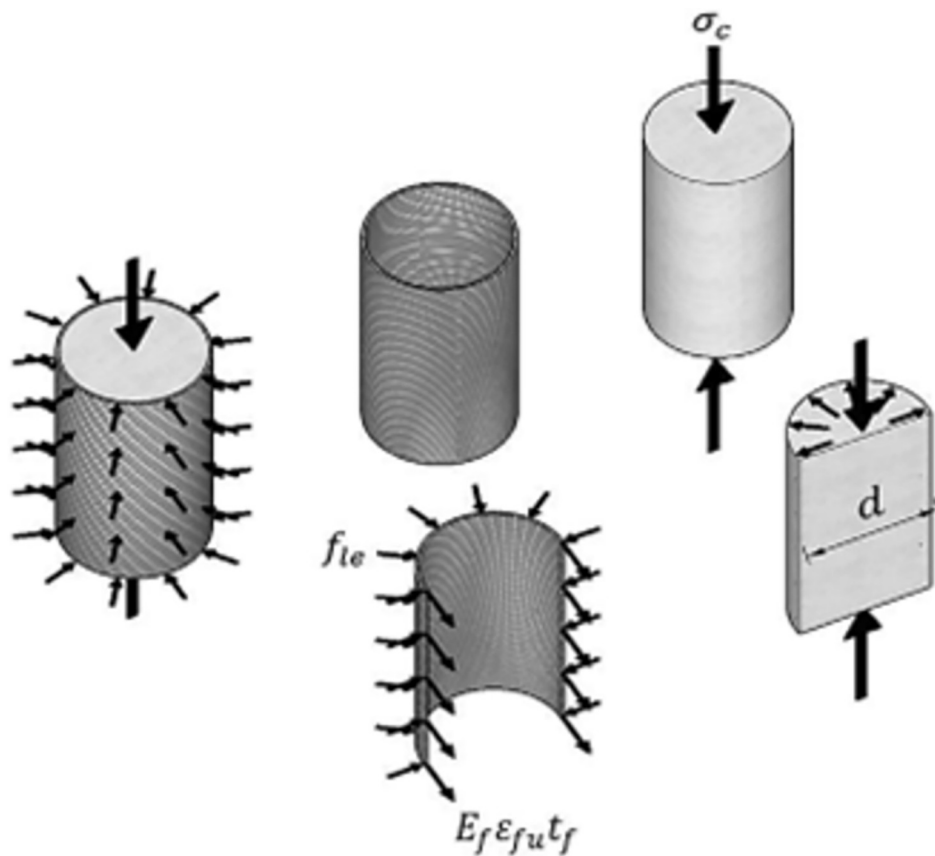


Fig 8. FRP lateral confining pressure and confining mechanism.

<https://doi.org/10.1371/journal.pone.0269664.g008>

according to Table 7. When compared to the values in Table 9, it is obvious that the CFRP lateral rupture strain measured on concrete surfaces differs from the equivalent tensile strain measurements obtained from coupons. According to Lam and Teng [49], local deformation at cracks in the concrete surface, the presence of the overlapping zone, and the FRP composite curvature are reasons that explain this discrepancy.

$$f_{le} = \frac{2nE_{frp}\epsilon_{he}t_{frp}}{d} \quad (2)$$

5.4. Strength model

The use of transverse steel reinforcements, such as spiral or circular ties, increases the strength and ductility of concrete. Several models for concrete confinement with FRP have been developed since the 1980s. Most of these models were based on the regression of test data and were accomplished on plain concrete specimens. Regardless of their classification, most proposed active confinement relationships use the confinement model given by [114, 115] based on tests of concrete samples confined with hydrostatic pressure. It was stated that the strength of confined concrete at failure, f'_{cc} , could be presented as a linear function of the lateral confining pressure, f'_{co} , as given in Eq (3). In this equation, the strength ratio or confinement effectiveness is f'_{cc} / f'_{co} , the confinement ratio is f_{le} / f'_{co} and k_1 is a confinement effectiveness

coefficient.

$$f'_{cc} = f'_{co} k_1 f_i \quad (3)$$

$$f'_{cc} = f'_{co} \left[1 + k_1 \frac{f_i}{f'_{co}} \right]$$

5.5. Evaluation of present strength models in prediction of f'_{cc}

Table 10 evaluates existing strength models to predict the strength of the CFRP wrapped concrete cylinders tested in this work. The precision of 47 proposed models from the literature was assessed. For direct comparison, the predictions of all models, including those provided in codes and guidelines to predict f'_{cc} have been supposed to potentially be adopted to the tested cylinders as part of this work. Note that the experimentally-measured strengths f'_{cc} were mostly initiated to differ from those predicted by the previously published models. These differences may be due to the following reasons: (i) Foil gauges at mid-height were used to measure strain values under ultimate conditions. (ii) The majority of the models were established from experiments on plain samples made of various FRP composites, and (iii) the value of f_{te} as labeled in Eq (2) was utilized rather than the f_i adopted in Eq (1). The foil gauges de-bonded in some cases prior to failure, so these data points aren't shown.

Of the models considered in Table 10, the models proposed by [68, 75, 78, 80, 116, 117] seem to provide a prediction of f'_{cc} which is closer to the control CFRP-confined test results declared in this paper. The models developed by [67, 74, 110, 118] were found to offer the closest prediction of f'_{cc} for all CFRP-confined cylinders containing PET waste established as part of this study. On the other hand, the models by [52, 53] greatly overestimate the compressive strength in comparison with the results of the present investigation.

The results clearly show that confinement effectiveness is reduced with increased unconfined concrete strength. The confinement effectiveness of CFRP for concrete with a lower unwrapped compressive strength exhibits a higher confinement ratio than that for higher strength concrete. As the compressive strength increases, the stiffness of concrete also increases, resulting in less lateral expansion before fracture of the CFRP wrapping occurs. Therefore, the concrete experiences less confining pressure.

The predicted strengths of the confined concrete (Table 10) are compared to the test outcomes, as shown in Fig 9. This figure demonstrates the generally poor correlation of model predictions for PET concrete confined with CFRP fabric.

6. Conclusions

Concrete containing PET has been used for essentially non-structural purposes where the element can support its weight. To determine whether PET concrete can be used for some structural applications, the behavior of concrete containing PET aggregates and confined with CFRP fabric was studied in this investigation. The main conclusions arising from this study are as follows:

1. When CFRP-wrapped cylinders failed, the values of hoop strains at failure on the surface were often lower than those in flat coupons.
2. Based on laboratory findings, PET plastic aggregate may be used as a partial substitute for sand for structural purposes, with a ratio of up to 50% by volume, combined with CFRP confinement. As the substitution rate of PET particles increases, the compressive strength decreases. All samples confined with CFRP fabrics for all mixtures showed a significant

Table 10. Evaluation of existing strength models to predict f'_{cc} , MPa.

No.	Author / Strength model	Group 1			Group 2			Group 3		
		R0WC40	R25WC40	R50WC40	R0WC45	R25WC45	R50WC45	R0WC55	R25WC55	R50WC55
		$f_{le} = 5.32$	$f_{le} = 7.98$	$f_{le} = 6.39$	$f_{le} = 7.45$	$f_{le} = 6.92$	$f_{le} = 5.86$	$f_{le} = 5.81$	$f_{le} = 7.39$	$f_{le} = 7.03$
		f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.
		86.81	71.98	40.81	82.10	65.67	34.09	69.97	67.04	35.45
		f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.
1	Richart et al. (1928) [115]	101.94	78.03	45.34	97.38	67.83	39.52	71.55	65.99	41.04
	$f'_{cc} = f'_{co} \left[1 + 4.1 \left(\frac{f_l}{f'_{co}} \right) \right]$									
2	Newman and Newman (1971) [119]	108.91	83.01	46.71	104.31	72.13	40.33	76.59	69.79	40.32
	$f'_{cc} = f'_{co} \left[1 + 3.7 \left(\frac{f_l}{f'_{co}} \right)^{0.86} \right]$									
3	Fardis and Khalili (1982) [51], GFRP, Adopted from Richart et al. (1928) [115]	101.94	78.03	45.34	97.38	67.83	39.52	71.55	65.99	41.04
4	Fafitis and Shah (1985) [120]	87.64	57.97	33.50	77.76	51.10	30.17	56.97	45.55	32.39
	$\frac{f'_{cc}}{f'_{co}} = 1 + \left(1.15 + \frac{21}{f'_{co}} \right) \frac{f_l}{f'_{co}}$									
5	Mander et al. (1988), steel-confined [53]	109.13	65.37	29.63	89.43	56.89	24.02	64.82	52.75	17.96
	$f'_{cc} = f'_{co} \left[-1.254 + 2.254 \sqrt{1 + 7.94 \left(\frac{f_l}{f'_{co}} - 2 \frac{f_l}{f'_{co}} \right)} \right]$									
6	Saatcioglu and Razvi (1992) [121]	106.96	82.87	50.38	102.31	72.83	44.56	76.59	70.94	46.02
	$f'_{cc} = f'_{co} + 6.7(f_l)^{0.83}$									
7	Eurocode 2 (1992) [122], FRP	103.45	70.92	37.51	93.81	61.69	32.08	68.22	58.64	31.31
	$f'_{cc} = f'_{co} \left(1.125 + 2.5 \frac{f_l}{f'_{co}} \right)$ for $f_l > 0.05 f'_{co}$									
8	Saadatmanesh et al. (1994) [52], CFRP & GFRP Adopted from Mander et al. (1988), steel-confined [53]	109.13	65.37	29.63	89.43	56.89	24.02	64.82	52.75	17.96
9	Cusson and Paultre (1995) [116], steel confined	86.89	54.29	26.83	75.39	47.59	22.73	54.93	44.22	20.43
	$f'_{cc} = f'_{co} + 2.1(f_{le})^{0.7}$									
10	Samaan et al. (1998) [118], FRP	99.46	70.98	41.12	91.30	62.70	36.18	68.29	60.04	35.71
	$f'_{cc} = f'_{co} + 6.0(f_l)^{0.7}$									
11	Miyauchi et al. (1999) [123], CFRP	95.98	69.10	38.18	89.03	60.08	32.96	65.05	57.73	33.16
	$f'_{cc} = f'_{co} \left[1 + 2.98 \left(\frac{f_l}{f'_{co}} \right) \right]$									
12	Saafi et al. (1999) [57], CFRP & GFRP	98.19	68.49	35.89	90.12	59.58	30.55	65.64	56.62	29.11
	$f'_{cc} = f'_{co} \left[1 + 2.2 \left(\frac{f_l}{f'_{co}} \right)^{0.84} \right]$									
13	Spoelstra and Monti (1999) [58], CFRP & GFRP	77.97	66.11	37.01	80.31	57.47	31.68	59.51	55.87	30.24
	$f'_{cc} = f'_{co} \left[0.2 + 3 \left(\frac{f_l}{f'_{co}} \right)^{0.5} \right]$									
14	Toutanji (1999) [59], GFRP & CFRP	108.01	81.55	45.51	103.07	70.91	39.22	75.62	68.46	38.94
	$f'_{cc} = f'_{co} \left[1 + 3.5 \left(\frac{f_l}{f'_{co}} \right)^{0.85} \right]$									
15	Xiao and Wu (2000) [60], CFRP	96.14	60.19	28.59	83.87	52.39	23.82	60.47	48.63	21.07
	$f'_{cc} = f'_{co} \left[1.1 + \left(\frac{f_l}{f'_{co}} \right)^{0.85} \right]$									
16	Lam and Teng (2001) [62], CFRP	90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
	$f'_{cc} = f'_{co} + 2f_l$									
17	Fam & Rizkalla (2001) [124], FRP, (adopted from Richart et al. (1928) [115])	101.94	78.03	45.34	97.38	67.83	39.52	71.55	65.99	41.04

(Continued)

Table 10. (Continued)

No.	Author / Strength model	Group 1			Group 2			Group 3		
		R0WC40	R25WC40	R50WC40	R0WC45	R25WC45	R50WC45	R0WC55	R25WC55	R50WC55
		$f_{ie} = 5.32$	$f_{ie} = 7.98$	$f_{ie} = 6.39$	$f_{ie} = 7.45$	$f_{ie} = 6.92$	$f_{ie} = 5.86$	$f_{ie} = 5.81$	$f_{ie} = 7.39$	$f_{ie} = 7.03$
		f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.
		86.81	71.98	40.81	82.10	65.67	34.09	69.97	67.04	35.45
18	Fib Bulletin TG (2001) [125], (adopted from Spoelstra and Monti (1999) [58])	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.
		77.97	66.11	37.01	80.31	57.47	31.68	59.51	55.87	30.24
		90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
		93.43	65.26	35.12	85.46	56.76	30.14	62.26	54.18	29.79
		109.13	65.37	29.63	89.43	56.89	24.02	64.82	52.75	17.96
19	Lin and Chen (2001) [61], GFRP & CFRP $f'_{cc} = f'_{co} + 2f_l$	99.65	63.08	33.37	83.42	54.87	28.54	60.67	52.16	27.87
		90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
		90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
		97.69	71.65	40.23	91.42	62.30	34.83	66.91	60.09	35.41
		99.46	70.98	41.12	91.30	62.70	36.18	68.29	60.04	35.71
20	ISIS Canada Guidelines (2001) [126] $f'_{cc} = f'_{co} \left[1 + 2.5 \left(\frac{f_l}{f_{co}} \right) \right]$	87.55	58.84	31.45	78.36	51.19	27.07	56.88	48.65	27.32
		114.29	82.33	43.09	107.08	71.61	36.56	78.21	68.18	34.18
		93.03	64.66	34.64	84.89	56.24	29.70	61.82	53.62	29.26
		101.94	78.03	45.34	97.38	67.83	39.52	71.55	65.99	41.04
		108.01	81.55	45.51	103.07	70.91	39.22	75.62	68.46	38.94
21	ACI 440.2R (2002) [127], adapted from Mander et al. (1988) [53]	97.03	72.84	41.19	91.06	63.33	35.71	67.78	61.20	36.46
		86.21	56.94	30.07	76.52	49.54	25.83	55.45	46.92	25.99
		92.22	61.36	35.62	82.13	56.89	31.01	60.58	53.95	29.84
		99.65	63.08	33.37	83.42	54.87	28.54	60.67	52.16	27.87
		90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
22	Ilki et al. (2002) [128], CFRP $f'_{cc} = f'_{co} \left[1 + 2.227 \left(\frac{f_l}{f_{co}} \right) \right]$	86.21	56.94	30.07	76.52	49.54	25.83	55.45	46.92	25.99
		92.22	61.36	35.62	82.13	56.89	31.01	60.58	53.95	29.84
		99.65	63.08	33.37	83.42	54.87	28.54	60.67	52.16	27.87
		90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
		97.69	71.65	40.23	91.42	62.30	34.83	66.91	60.09	35.41
23	Lam and Teng (2002) [64], GFRP & CFRP $f'_{cc} = f'_{co} + 2f_l$	86.21	56.94	30.07	76.52	49.54	25.83	55.45	46.92	25.99
		92.22	61.36	35.62	82.13	56.89	31.01	60.58	53.95	29.84
		99.65	63.08	33.37	83.42	54.87	28.54	60.67	52.16	27.87
		90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
		97.69	71.65	40.23	91.42	62.30	34.83	66.91	60.09	35.41
24	Shehata et al. (2002) [65], CFRP $f'_{cc} = f'_{co} \left[1 + 2 \left(\frac{f_l}{f_{co}} \right) \right]$	86.21	56.94	30.07	76.52	49.54	25.83	55.45	46.92	25.99
		92.22	61.36	35.62	82.13	56.89	31.01	60.58	53.95	29.84
		99.65	63.08	33.37	83.42	54.87	28.54	60.67	52.16	27.87
		90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
		97.69	71.65	40.23	91.42	62.30	34.83	66.91	60.09	35.41
25	Lam and Teng (2003) [110], FRP $\frac{f'_{cc}}{f'_{co}} = 1 + 3.3 \frac{f_l}{f_{co}}$	86.21	56.94	30.07	76.52	49.54	25.83	55.45	46.92	25.99
		92.22	61.36	35.62	82.13	56.89	31.01	60.58	53.95	29.84
		99.65	63.08	33.37	83.42	54.87	28.54	60.67	52.16	27.87
		90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
		97.69	71.65	40.23	91.42	62.30	34.83	66.91	60.09	35.41
26	De Lorenzis and Tepfers (2003) [67], FRP, nominated the ultimate strength expressions by Samaan et al. (1998) [118], Toutanji (1999) [59], and Spoelstra and Monti (1999) [58], ('approximate' model)	86.21	56.94	30.07	76.52	49.54	25.83	55.45	46.92	25.99
		92.22	61.36	35.62	82.13	56.89	31.01	60.58	53.95	29.84
		99.65	63.08	33.37	83.42	54.87	28.54	60.67	52.16	27.87
		90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
		97.69	71.65	40.23	91.42	62.30	34.83	66.91	60.09	35.41
27	Ilki et al. (2004) [68], CFRP $\frac{f'_{cc}}{f'_{co}} = 1 + 2.4 \left(\frac{f'_{lmax}}{f_{co}} \right)^{1.2}$	86.21	56.94	30.07	76.52	49.54	25.83	55.45	46.92	25.99
		92.22	61.36	35.62	82.13	56.89	31.01	60.58	53.95	29.84
		99.65	63.08	33.37	83.42	54.87	28.54	60.67	52.16	27.87
		90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
		97.69	71.65	40.23	91.42	62.30	34.83	66.91	60.09	35.41
28	CNR-DT 200 (2004) [129] $\frac{f'_{cc}}{f'_{co}} = 1 + 2.6 \left(\frac{f'_{lmax}}{f_{co}} \right)^{2/3}$	86.21	56.94	30.07	76.52	49.54	25.83	55.45	46.92	25.99
		92.22	61.36	35.62	82.13	56.89	31.01	60.58	53.95	29.84
		99.65	63.08	33.37	83.42	54.87	28.54	60.67	52.16	27.87
		90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
		97.69	71.65	40.23	91.42	62.30	34.83	66.91	60.09	35.41
29	Bisby et al. (2005) [69], CFRP $f'_{cc} = f'_{co} \left[1 + 2.425 \left(\frac{f_l}{f_{co}} \right) \right]$	86.21	56.94	30.07	76.52	49.54	25.83	55.45	46.92	25.99
		92.22	61.36	35.62	82.13	56.89	31.01	60.58	53.95	29.84
		99.65	63.08	33.37	83.42	54.87	28.54	60.67	52.16	27.87
		90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
		97.69	71.65	40.23	91.42	62.30	34.83	66.91	60.09	35.41
30	Harajli (2006) [71], CFRP (adopted from Richart et al. (1928) [115])	86.21	56.94	30.07	76.52	49.54	25.83	55.45	46.92	25.99
		92.22	61.36	35.62	82.13	56.89	31.01	60.58	53.95	29.84
		99.65	63.08	33.37	83.42	54.87	28.54	60.67	52.16	27.87
		90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
		97.69	71.65	40.23	91.42	62.30	34.83	66.91	60.09	35.41
31	Matthys et al. (2006) [73], hybrid FRP, CFRP & GFRP (adopted from Toutanji (1999) [59])	86.21	56.94	30.07	76.52	49.54	25.83	55.45	46.92	25.99
		92.22	61.36	35.62	82.13	56.89	31.01	60.58	53.95	29.84
		99.65	63.08	33.37	83.42	54.87	28.54	60.67	52.16	27.87
		90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
		97.69	71.65	40.23	91.42	62.30	34.83	66.91	60.09	35.41
32	Berthet, et al. (2006) [74], GFRP, CFRP, $f'_{cc} = f'_{co} + k_1 f_l$ $k_1 = 3.45$ if $20 \text{ MPa} \leq f'_{co} \leq 50 \text{ MPa}$ $k_1 = 9.5 / (f'_{co})^{0.25}$ if $50 \text{ MPa} \leq f'_{co} \leq 200 \text{ MPa}$	86.21	56.94	30.07	76.52	49.54	25.83	55.45	46.92	25.99
		92.22	61.36	35.62	82.13	56.89	31.01	60.58	53.95	29.84
		99.65	63.08	33.37	83.42	54.87	28.54	60.67	52.16	27.87
		90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
		97.69	71.65	40.23	91.42	62.30	34.83	66.91	60.09	35.41
33	Youssef et al. (2007) [75], GFRP & CFRP $f'_{cc} = f'_{co} \left[1 + 2.25 \left(\frac{f_l}{f_{co}} \right)^{1.25} \right]$	86.21	56.94	30.07	76.52	49.54	25.83	55.45	46.92	25.99
		92.22	61.36	35.62	82.13	56.89	31.01	60.58	53.95	29.84
		99.65	63.08	33.37	83.42	54.87	28.54	60.67	52.16	27.87
		90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
		97.69	71.65	40.23	91.42	62.30	34.83	66.91	60.09	35.41
34	Fahmy and Wu (2010) [77], $f'_{cc} = f'_{co} + k_1 f_l^{0.7}$ $k_1 = 3.75 f'_{co} > 40 \text{ MPa}$, $k_1 = 4.5 f'_{co} \leq 40 \text{ MPa}$	86.21	56.94	30.07	76.52	49.54	25.83	55.45	46.92	25.99
		92.22	61.36	35.62	82.13	56.89	31.01	60.58	53.95	29.84
		99.65	63.08	33.37	83.42	54.87	28.54	60.67	52.16	27.87
		90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
		97.69	71.65	40.23	91.42	62.30	34.83	66.91	60.09	35.41

(Continued)

Table 10. (Continued)

No.	Author / Strength model	Group 1			Group 2			Group 3		
		R0WC40	R25WC40	R50WC40	R0WC45	R25WC45	R50WC45	R0WC55	R25WC55	R50WC55
		$f_{ie} = 5.32$	$f_{ie} = 7.98$	$f_{ie} = 6.39$	$f_{ie} = 7.45$	$f_{ie} = 6.92$	$f_{ie} = 5.86$	$f_{ie} = 5.81$	$f_{ie} = 7.39$	$f_{ie} = 7.03$
		f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.	f'_{cc} Exp.
		86.81	71.98	40.81	82.10	65.67	34.09	69.97	67.04	35.45
		f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.	f'_{cc} Pred.
35	Benzaid et al. (2010) [78]	88.64	58.08	29.36	78.75	50.53	24.87	57.03	47.53	23.46
	$f'_{cc} = f'_{co} \left[1 + 1.6 \left(\frac{f_l}{f'_{co}} \right) \right]$									
36	Lee et al. (2010) [79]	90.77	61.27	31.92	81.73	53.30	27.21	59.35	50.48	26.27
	$f'_{cc} = f'_{co} \left(1 + 2 \left(\frac{f_l}{f'_{co}} \right) \right)$									
37	Mohamed and Masmoudi (2010) [117], FRP	88.49	67.99	37.38	85.63	59.12	32.03	62.92	56.99	30.95
	$f'_{cc} = f'_{co} \left[0.7 + 2.7 \left(\frac{f_l}{f'_{co}} \right)^{0.7} \right]$									
38	Xiao et al. (2010) [130], FRP	109.78	81.91	44.92	104.26	71.22	38.55	76.42	68.51	37.65
	$\frac{f'_{cc}}{f'_{co}} = 1 + 3.24 \left(\frac{f_l}{f'_{co}} \right)^{0.8}$									
39	Ghernouti and Rabehi (2011) [80]	85.88	53.93	26.04	74.88	46.94	21.82	54.01	43.68	19.80
	$\frac{f'_{cc}}{f'_{co}} = 1 + 1.08 \left(\frac{f_l}{f'_{co}} \right)$									
40	Ozbakkaloglu and Lim, (2013) [82], CFRP	99.49	74.36	42.40	93.95	64.65	36.82	68.88	62.60	37.80
	$\frac{f'_{cc}}{f'_{co}} = 1 + 3.64 \left(\frac{f_l}{f'_{co}} \right)$									
41	Afifi et al. (2015) [131], CFRP	106.12	66.81	30.79	93.36	58.16	25.39	67.34	53.74	21.41
	$\frac{f'_{cc}}{f'_{co}} = 1 + 0.934 \left(\frac{f_l}{f'_{co}} \right)^{0.39}$									
42	Kwan et al. (2015) [132], FRP (adopted from Xiao et al. (2010) [130])	109.78	81.91	44.92	104.26	71.22	38.55	76.42	68.51	37.65
43	Huang, et al. (2016), GFRP	104.66	70.95	35.35	95.18	61.73	29.68	69.14	58.01	26.78
	$\frac{f'_{cc}}{f'_{co}} = 1 + 1.69 \left(\frac{f_l}{f'_{co}} \right)^{0.63}$									
44	Touhari and Mitiche-Kettab (2016) [93], CFRP	95.03	67.65	37.03	87.69	58.84	31.89	64.00	56.39	31.89
	$\frac{f'_{cc}}{f'_{co}} = 1 + 2.8 \left(\frac{f_l}{f'_{co}} \right)$									
45	Ahmed (2018) [133], FRP	89.44	59.28	30.33	79.87	51.57	25.77	57.89	48.63	24.52
	$\frac{f'_{cc}}{f'_{co}} = 1 + 1.75 \left(\frac{f_l}{f'_{co}} \right)$									
46	Raza et al. (2020) [134], FRP	111.57	82.26	44.36	105.51	71.54	37.06	77.24	68.57	36.42
	$f_{cc} = f'_{co} + 3f'_{co} \left(\frac{f_l}{f'_{co}} \right)^{3/4}$									
47	Hussain et al. (2020) [135], FRRP	94.49	66.86	36.39	86.95	58.15	31.31	63.42	55.65	31.19
	$\frac{f'_{cc}}{f'_{co}} = 1 + 2.70 \left(\frac{f_l}{f'_{co}} \right)$									

<https://doi.org/10.1371/journal.pone.0269664.t010>

enhancement in strength compared to non-confined samples for the same proportions of substitution. The enhancement ratio ranged from 8% to 190%.

- For cylinders confined with CFRP, as the replacement ratio increases, there is a decrease in the initial slope of the axial -strain curve and-strain curve and the value of stress at which the stress-strain curve ceases to be linear. Note that the slope of the non-linear part of the axial stress-strain curve is always positive due to the confining pressure, which increases rapidly due to the rapid increase in lateral dilation of the concrete.

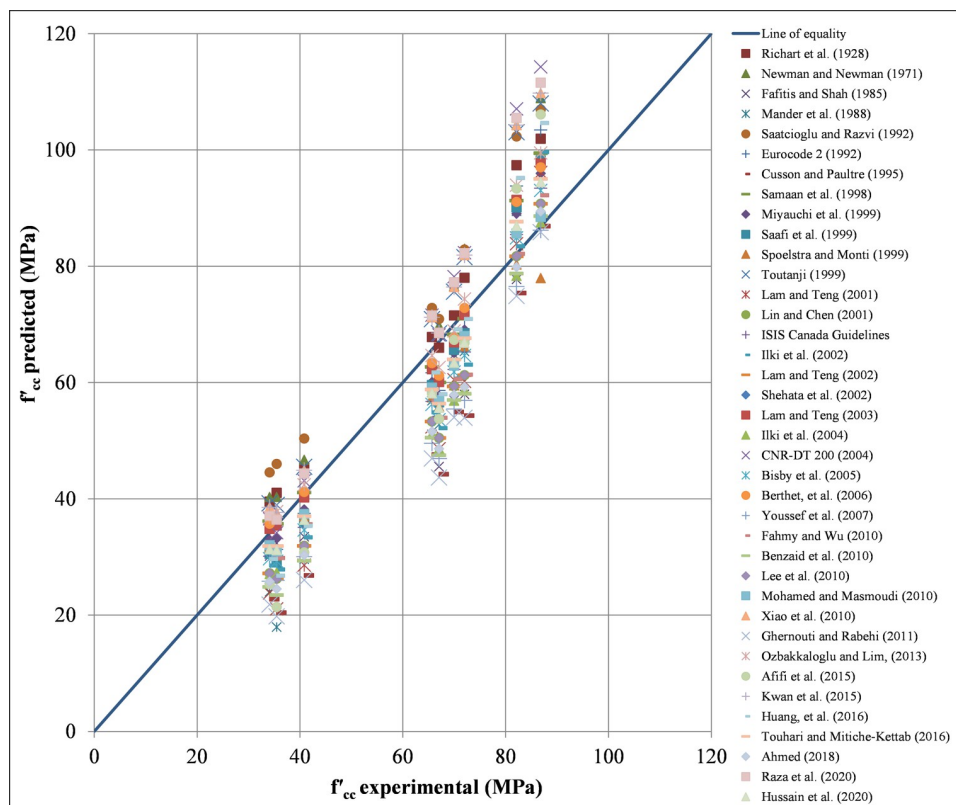


Fig 9. Experimental results vs. predicted values for maximum stress in confined concrete.

<https://doi.org/10.1371/journal.pone.0269664.g009>

4. The addition of a single layer of CFRP fabric wrap increased the ultimate load of samples to a level not less than that of unconfined samples without PET plastic waste. The recovery ratio ranged from 51% to 140%.
5. All of the samples that were confined failed because of the tensile failure of the CFRP fabric. The failure happened near the mid-height area outside of the overlapped area.
6. A comparison of the ultimate strength f'_{cc} predicted by the range of confined concrete models found in the literature and test strengths was undertaken. It was noticed that these models do not offer a satisfactory prediction of the ultimate strength of PET concrete confined by CFRP fabric. However, the models confirmed that both confinement effectiveness (f'_{cc} / f'_{co}) and confinement ratio (f_{te} / f'_{co}) increase with increasing PET substitution.

Author Contributions

Conceptualization: Shaker Qaidi, Yaman S. S. Al-Kamaki, Haytham F. Isleem.

Data curation: Hemn Unis Ahmed, Fadi Althoei, Jawad Ahmad.

Investigation: Shaker Qaidi, Osama Zaid.

Methodology: Riadh Al-Mahaidi, Hemn Unis Ahmed.

Project administration: Ahmed S. Mohammed, Fadi Althoei.

Resources: Ian Bennetts.

Software: Yaman S. S. Al-Kamaki, Osama Zaid.

Supervision: Riadh Al-Mahaidi.

Validation: Jawad Ahmad.

Visualization: Haytham F. Isleem.

Writing – original draft: Shaker Qaidi, Ahmed S. Mohammed, Haytham F. Isleem.

Writing – review & editing: Yaman S. S. Al-Kamaki, Riadh Al-Mahaidi, Ahmed S. Mohammed, Ian Bennetts.

References

1. Kore Sudarshan D, Vyas AK. Impact of fire on mechanical properties of concrete containing marble waste. *Journal of King Saud University—Engineering Sciences*. 2019; 31(1):42–51. <https://doi.org/10.1016/j.jksues.2017.03.007>.
2. Ahmed HU, Mohammed AA, Rafiq S, Mohammed AS, Mosavi A, Sor NH, et al. Compressive Strength of Sustainable Geopolymer Concrete Composites: A State-of-the-Art Review. *Sustainability*. 2021; 13(24):13502. <https://doi.org/10.3390/su132413502>
3. Qaidi SMA, Tayeh BA, Zeyad AM, de Azevedo ARG, Ahmed HU, Emad W. Recycling of mine tailings for the geopolymers production: A systematic review. *Case Studies in Construction Materials*. 2022; 16:e00933. <https://doi.org/10.1016/j.cscm.2022.e00933>.
4. Silva RV, de Brito J, Saikia N. Influence of curing conditions on the durability-related performance of concrete made with selected plastic waste aggregates. *Cement and Concrete Composites*. 2013; 35(1):23–31. <https://doi.org/10.1016/j.cemconcomp.2012.08.017>.
5. Heredia NV. Incorporation of waste polyethylene terephthalate (PET) into concrete using statistical mixture design. Memorial University of Newfoundland: Memorial University of Newfoundland; 2018.
6. Ahmed SN, Hamah Sor N, Ahmed MA, Qaidi SMA. Thermal conductivity and hardened behavior of eco-friendly concrete incorporating waste polypropylene as fine aggregate. *Materials Today: Proceedings*. 2022; 57:818–23. <https://doi.org/10.1016/j.matpr.2022.02.417>.
7. Qaidi SMA. Behavior of Concrete Made of Recycled PET Waste and Confined with CFRP Fabrics: College of Engineering, University of Duhok; 2021.
8. Rahmani E, Dehestani M, Beygi MHA, Allahyari H, Nikbin IM. On the mechanical properties of concrete containing waste PET particles. *Construction and Building Materials*. 2013; 47:1302–8. <https://doi.org/10.1016/j.conbuildmat.2013.06.041>.
9. Almeshal I, Al-Tayeb MM, Qaidi SMA, Abu Bakar BH, Tayeh BA. Mechanical properties of eco-friendly cements-based glass powder in aggressive medium. *Materials Today: Proceedings*. 2022. <https://doi.org/10.1016/j.matpr.2022.03.613>.
10. Ahmed HU, Mohammed AS, Faraj RH, Qaidi SMA, Mohammed AA. Compressive strength of geopolymer concrete modified with nano-silica: Experimental and modeling investigations. *Case Studies in Construction Materials*. 2022; 16:e01036. <https://doi.org/10.1016/j.cscm.2022.e01036>.
11. Mansi A, Sor NH, Hilal N, Qaidi SM, editors. *The Impact of Nano Clay on Normal and High-Performance Concrete Characteristics: A Review*. IOP Conference Series: Earth and Environmental Science; 2022: IOP Publishing.
12. Umair M, Khan MI, Nawab Y. Green Fiber-Reinforced Concrete Composites. *Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications*. 2020:1–32.
13. Khan MI, Umair M, Shaker K, Basit A, Nawab Y, Kashif M. Impact of waste fibers on the mechanical performance of concrete composites. *The Journal of The Textile Institute*. 2020; 111(11):1632–40.
14. Qaidi SMA, Al-Kamaki YSS. State-of-the-Art Review: Concrete Made of Recycled Waste PET as Fine Aggregate. *Journal of Duhok University*. 2021; 23(2):412–29.
15. Mohammadhosseini H, Tahir MM, Alaskar A, Alabduljabbar H, Alyousef R. Enhancement of strength and transport properties of a novel preplaced aggregate fiber reinforced concrete by adding waste polypropylene carpet fibers. *Journal of Building Engineering*. 2020; 27:101003. <https://doi.org/10.1016/j.jobbe.2019.101003>.
16. ACI, editor ACI 544.1 R-96: Report on Fiber Reinforced Concrete 2002: American Concrete Institute Farmington Hills, MI, USA.
17. Al-Hadithi AI, Abbas MA. The effects of adding waste plastic fibers on the mechanical properties and shear strength of reinforced concrete beams. *Iraqi Journal of Civil Engineering*. 2018; 12(1):110–24.

18. Al-Manaseer A, Dalal T. Concrete containing plastic aggregates. *Concrete International*. 1997; 19(8):47–52.
19. Agamuthu P, Faizura PN. Biodegradability of degradable plastic waste. *Waste Management & Research*. 2005; 23(2):95–100. <https://doi.org/10.1177/0734242X05051045> PMID: 15864950
20. Kim SB, Yi NH, Kim HY, Kim J-HJ, Song Y-C. Material and structural performance evaluation of recycled PET fiber reinforced concrete. *Cement and Concrete Composites*. 2010; 32(3):232–40. <https://doi.org/10.1016/j.cemconcomp.2009.11.002>.
21. Bajracharya RM, Manalo AC, Karunasena W, Lau K-t. An overview of mechanical properties and durability of glass-fibre reinforced recycled mixed plastic waste composites. *Materials & Design* (1980–2015). 2014; 62:98–112. <https://doi.org/10.1016/j.matdes.2014.04.081>.
22. Babafemi AJ, Šavija B, Paul SC, Anggraini V. Engineering properties of concrete with waste recycled plastic: a review. *Sustainability*. 2018; 10(11):3875.
23. Kore SD. Sustainable utilization of plastic waste in concrete mixes-a review. *Journal of Building Materials and Structures*. 2018; 5(2):212–7.
24. Qaidi SMA, Tayeh BA, Isleem HF, de Azevedo ARG, Ahmed HU, Emad W. Sustainable utilization of red mud waste (bauxite residue) and slag for the production of geopolymer composites: A review. *Case Studies in Construction Materials*. 2022; 16:e00994. <https://doi.org/10.1016/j.cscm.2022.e00994>.
25. Khalil KJ. Studying the utilization of polymeric wastes to produce sustainable concrete: MSc. Thesis, Building & Construction Dept., Univ. of Technology, Iraq; 2015.
26. Qaidi SMA, Dinkha YZ, Haido JH, Ali MH, Tayeh BA. Engineering properties of sustainable green concrete incorporating eco-friendly aggregate of crumb rubber: A review. *Journal of Cleaner Production*. 2021; 324:129251. <https://doi.org/10.1016/j.jclepro.2021.129251>.
27. Faraj RH, Ahmed HU, Rafiq S, Sor NH, Ibrahim DF, Qaidi SMA. Performance of Self-Compacting Mortars Modified with Nanoparticles: A Systematic Review and Modeling. *Cleaner Materials*. 2022:100086. <https://doi.org/10.1016/j.clema.2022.100086>.
28. Jawad Ahmad FA, Martinez-Garcia Rebeca, de-Prado-Gil Jesús, Qaidi Shaker M. A., Brahmia Ameni. Effects of waste glass and waste marble on mechanical and durability performance of concrete. *Scientific Reports*. 2021; 11(1):21525. <https://doi.org/10.1038/s41598-021-00994-0> PMID: 34728731
29. Albano C, Camacho N, Hernández M, Matheus A, Gutiérrez A. Influence of content and particle size of waste pet bottles on concrete behavior at different w/c ratios. *Waste Management*. 2009; 29(10):2707–16. <https://doi.org/10.1016/j.wasman.2009.05.007> PMID: 19525104
30. Ragaert K, Delva L, Van Geem K. Mechanical and chemical recycling of solid plastic waste. *Waste Management*. 2017; 69:24–58. <https://doi.org/10.1016/j.wasman.2017.07.044> PMID: 28823699
31. Modro N, Modro N, Oliveira A. Evaluation of concrete made of Portland cement containing PET wastes. *Matéria (Rio de Janeiro)*. 2009; 14(1):725–36.
32. Pacheco-Torgal F, Ding Y, Jalali S. Properties and durability of concrete containing polymeric wastes (tyre rubber and polyethylene terephthalate bottles): An overview. *Construction and Building Materials*. 2012; 30:714–24. <https://doi.org/10.1016/j.conbuildmat.2011.11.047>.
33. Marzouk OY, Dheilly RM, Queneudec M. Valorization of post-consumer waste plastic in cementitious concrete composites. *Waste Management*. 2007; 27(2):310–8. <https://doi.org/10.1016/j.wasman.2006.03.012> PMID: 16730969
34. Batayneh M, Marie I, Asi I. Use of selected waste materials in concrete mixes. *Waste Management*. 2007; 27(12):1870–6. Epub 2006/11/07. <https://doi.org/10.1016/j.wasman.2006.07.026> PMID: 17084070.
35. Ismail ZZ, Al-Hashmi EA. Use of waste plastic in concrete mixture as aggregate replacement. *Waste Management*. 2008; 28(11):2041–7. <https://doi.org/10.1016/j.wasman.2007.08.023> PMID: 17931848
36. Kou SC, Lee G, Poon CS, Lai WL. Properties of lightweight aggregate concrete prepared with PVC granules derived from scraped PVC pipes. *Waste Management*. 2009; 29(2):621–8. <https://doi.org/10.1016/j.wasman.2008.06.014> PMID: 18691863
37. Choi YW, Moon DJ, Kim YJ, Lachemi M. Characteristics of mortar and concrete containing fine aggregate manufactured from recycled waste polyethylene terephthalate bottles. *Construction and Building Materials*. 2009; 23(8):2829–35. <https://doi.org/10.1016/j.conbuildmat.2009.02.036>.
38. Frigione M. Recycling of PET bottles as fine aggregate in concrete. *Waste Management*. 2010; 30(6):1101–6. <https://doi.org/10.1016/j.wasman.2010.01.030> PMID: 20176466
39. Hannawi K, Kamali-Bernard S, Prince W. Physical and mechanical properties of mortars containing PET and PC waste aggregates. *Waste Management*. 2010; 30(11):2312–20. <https://doi.org/10.1016/j.wasman.2010.03.028> PMID: 20417085

40. Rai B, Rushad ST, Kr B, Duggal S. Study of waste plastic mix concrete with plasticizer. *International Scholarly Research Notices*. 2012; 2012:1–5.
41. Wang R, Meyer C. Performance of cement mortar made with recycled high impact polystyrene. *Cement and Concrete Composites*. 2012; 34(9):975–81. <https://doi.org/10.1016/j.cemconcomp.2012.06.014>.
42. Ge Z, Sun R, Zhang K, Gao Z, Li P. Physical and mechanical properties of mortar using waste Polyethylene Terephthalate bottles. *Construction and Building Materials*. 2013; 44:81–6. <https://doi.org/10.1016/j.conbuildmat.2013.02.073>.
43. Juki MI, Muhamad K, Annas MMK, Boon KH, Othman N, Asyraf R, et al., editors. Development of concrete mix design nomograph containing polyethylene terephthalate (PET) as fine aggregate. *Advanced Materials Research*; 2013: Trans Tech Publ.
44. Ávila Córdoba L, Martínez-Barrera G, Barrera Díaz C, Ureña Nuñez F, Loza Yañez A. Effects on Mechanical Properties of Recycled PET in Cement-Based Composites. *International Journal of Polymer Science*. 2013; 2013:763276. <https://doi.org/10.1155/2013/763276>
45. Saikia N, de Brito J. Mechanical properties and abrasion behaviour of concrete containing shredded PET bottle waste as a partial substitution of natural aggregate. *Construction and Building Materials*. 2014; 52:236–44. <https://doi.org/10.1016/j.conbuildmat.2013.11.049>.
46. Azhdarpour AM, Nikoudeh MR, Taheri M. The effect of using polyethylene terephthalate particles on physical and strength-related properties of concrete; a laboratory evaluation. *Construction and Building Materials*. 2016; 109:55–62. <https://doi.org/10.1016/j.conbuildmat.2016.01.056>.
47. Al-Hadithi AI, Alani MF, editors. Importance of adding waste plastics to high-performance concrete. *Proceedings of the Institution of Civil Engineers-Waste and Resource Management*; 2018: Thomas Telford Ltd.
48. Almeshal I, Tayeh BA, Alyousef R, Alabduljabbar H, Mohamed AM. Eco-friendly concrete containing recycled plastic as partial replacement for sand. *Journal of Materials Research and Technology*. 2020; 9(3):4631–43. <https://doi.org/10.1016/j.jmrt.2020.02.090>.
49. Lam L, Teng JG. Ultimate condition of fiber reinforced polymer-confined concrete. *Journal of Composites for Construction*. 2004; 8(6):539–48.
50. Wei H, Wu Z, Guo X, Yi F. Experimental study on partially deteriorated strength concrete columns confined with CFRP. *Engineering Structures*. 2009; 31(10):2495–505.
51. Fardis MN, Khalili HH. FRP-encased concrete as a structural material. *Magazine of Concrete Research*. 1982; 34(121):191–202.
52. Saadatmanesh H, Ehsani MR, Li MW. Strength and ductility of concrete columns externally reinforced with fiber composite straps. *ACI Structural Journal*. 1994; 91(4):434–47.
53. Mander JB, Priestley MJN, Park R. Theoretical stress-strain model for confined concrete. *Journal of Structural Engineering* 1988; 114(8):1804–26.
54. Mander JB, Priestley MJN, Park R. Observed stress-strain behavior of confined concrete. *Journal of Structural Engineering* 1988; 114(8):1827–49.
55. Karbhari VM, Gao Y. Composite jacketed concrete under uniaxial compression—Verification of simple design equations. *Journal of Materials in Civil Engineering*. 1997; 9(4):185–93.
56. Samaan MS. An analytical and experimental investigation of concrete-filled-fiber reinforced plastics (FRP) tubes: University of Central Florida, Orlando, Florida; 1997.
57. Saafi M, Toutanji HA, Li Z. Behavior of concrete columns confined with fiber reinforced polymer tubes. *ACI Materials Journal*. 1999; 96(4):500–9.
58. Spoelstra MR, Monti G. FRP-confined concrete model. *Journal of Composites for Construction*. 1999; 3(3):143–50.
59. Toutanji HA. Stress-strain characteristics of concrete columns externally confined with advanced fiber composite sheets. *ACI Materials Journal*. 1999; 96(3):397–404.
60. Xiao Y, Wu H. Compressive behavior of concrete confined by carbon fiber composite jackets. *Journal of Materials in Civil Engineering*. 2000; 12(2):139–46.
61. Lin HJ, Chen CT. Strength of concrete cylinder confined by composite materials. *Journal of Reinforced Plastics and Composites*. 2001; 20(18):1577–600.
62. Lam L, Teng JG, editors. A new stress-strain model for FRP-confined concrete. *FRP Composites in Civil Engineering, Vols I and II, Proceedings*; 2001; Hong Kong Polytechnic University, Hong Kong, China: FRP Composites in Civil Engineering.
63. Ilki A, Kumbasar N, Koc V, editors. Strength and deformability of low strength concrete confined by carbon fiber composite sheets. *Proceedings of the 15th ASCE Engineering Mechanics Conference, New York, On CD Paper, no 101*; 2002.

64. Lam L, Teng JG. Strength models for fiber-reinforced plastic-confined concrete. *Journal of Structural Engineering*. 2002; 128(5):612–23.
65. Shehata IAEM, Carneiro LAV, Shehata LCD. Strength of short concrete columns confined with CFRP sheets. *Materials and Structures/Materiaux et Constructions*. 2002; 34(245):50–8.
66. Chaallal O, Hassan M, Shahawy M. Confinement model for axially loaded short rectangular columns strengthened with fiber-reinforced polymer wrapping. *ACI Structural Journal*. 2003; 100(2):215–21.
67. De Lorenzis L, Tepfers R. Comparative study of models on confinement of concrete cylinders with fiber-reinforced polymer composites. *Journal of Composites for Construction*. 2003; 7(3):219–37.
68. Ilki A, Kumbasar N, Koc V. Low strength concrete members externally confined with FRP sheets. *Structural Engineering and Mechanics*. 2004; 18(2):167–94.
69. Bisby LA, Dent AJS, Green MF. Comparison of confinement models for fiber-reinforced polymer-wrapped concrete. *ACI Structural Journal*. 2005; 102(1):62–72.
70. Tamuzs V, Tepfers R, Sparnins E. Behavior of concrete cylinders confined by carbon composite 2. Prediction of strength. *Mechanics of Composite Materials*. 2006; 42(2):109–18.
71. Harajli MH. Axial stress-strain relationship for FRP confined circular and rectangular concrete columns. *Cement and Concrete Composites*. 2006; 28(10):938–48.
72. Ilki A, Peker O, Karamuk E, Demir C, Kumbasar N. Axial behavior of RC columns retrofitted with FRP composites. *Advances in Earthquake Engineering for Urban Risk Reduction. NATO Science Series IV Earth and Environmental Sciences*. 2006; 66. p. 301–16.
73. Matthys S, Toutanji H, Taerwe L. Stress-strain behavior of large-scale circular columns confined with FRP composites. *Journal of Structural Engineering*. 2006; 132(1):123–33.
74. Berthet JF, Ferrier E, Hamelin P. Compressive behavior of concrete externally confined by composite jackets: Part B: Modeling. *Construction and Building Materials*. 2006; 20(5):338–47.
75. Youssef MN, Feng MQ, Mosallam AS. Stress-strain model for concrete confined by FRP composites. *Composites Part B: Engineering*. 2007; 38(5–6):614–28.
76. Rousakis TC, Karabinis AI. Substandard reinforced concrete members subjected to compression: FRP confining effects. *Materials and Structures/Materiaux et Constructions*. 2008; 41(9):1595–611.
77. Fahmy MFM, Wu Z. Evaluating and proposing models of circular concrete columns confined with different FRP composites. *Composites Part B: Engineering*. 2010; 41(3):199–213.
78. Benzaid R, Mesbah H, Nasr Eddine C. FRP-confined concrete cylinders: Axial compression experiments and strength model. *Journal of Reinforced Plastics and Composites*. 2010; 29(16):2469–88.
79. Lee JY, Yi CK, Jeong HS, Kim SW, Kim JK. Compressive response of concrete confined with steel spirals and FRP composites. *Journal of Composite Materials*. 2010; 44(4):481–504.
80. Ghernouti Y, Rabehi B. FRP-confined short concrete columns under compressive loading: Experimental and modeling investigation. *Journal of Reinforced Plastics and Composites*. 2011; 30(3):241–55.
81. Rousakis TC, Rakitzis TD, Karabinis AI. Design-oriented strength model for FRP confined concrete members. *Journal of Composites for Construction*. 2012:615–25.
82. Ozbakkaloglu T, Lim JC, Vincent T. FRP-confined concrete in circular sections: Review and assessment of stress-strain models. *Engineering Structures*. 2013; 49:1068–88.
83. Huang L, Gao C, Yan L, Kasal B, Ma G, Tan H. Confinement models of GFRP-confined concrete: Statistical analysis and unified stress-strain models. *Journal of Reinforced Plastics and Composites*. 2016; 35(11):867–91. <https://doi.org/10.1177/0731684416630609>
84. Moodi Y, Mousavi SR, Sohrabi MR. New models for estimating compressive strength of concrete confined with FRP sheets in circular sections. *Journal of Reinforced Plastics and Composites*. 2019; 38(21–22):1014–28. <https://doi.org/10.1177/0731684419858708>
85. Guo Y-C, Gao W-Y, Zeng J-J, Duan Z-J, Ni X-Y, Peng K-D. Compressive behavior of FRP ring-confined concrete in circular columns: Effects of specimen size and a new design-oriented stress-strain model. *Construction and Building Materials*. 2019; 201:350–68. <https://doi.org/10.1016/j.conbuildmat.2018.12.183>.
86. Zeng J-J, Guo Y-C, Gao W-Y, Chen W-P, Li L-J. Stress-strain behavior of concrete in circular concrete columns partially wrapped with FRP strips. *Composite Structures*. 2018; 200:810–28. <https://doi.org/10.1016/j.compstruct.2018.05.001>.
87. Fallah Pour A, Ozbakkaloglu T, Vincent T. Simplified design-oriented axial stress-strain model for FRP-confined normal- and high-strength concrete. *Engineering Structures*. 2018; 175:501–16. <https://doi.org/10.1016/j.engstruct.2018.07.099>.
88. Djafar-Henni I, Kassoul A. Stress-strain model of confined concrete with Aramid FRP wraps. *Construction and Building Materials*. 2018; 186:1016–30. <https://doi.org/10.1016/j.conbuildmat.2018.08.013>.

89. Del Zoppo M, Di Ludovico M, Balsamo A, Prota A. Comparative analysis of existing RC columns jacketed with CFRP or FRCC. *Polymers*. 2018; 10(4):1–20. <https://doi.org/10.3390/polym10040361> PMID: 30966396
90. Hadhood A, Mohamed HM, Benmokrane B. Strength of circular HSC columns reinforced internally with carbon-fiber-reinforced polymer bars under axial and eccentric loads. *Construction and Building Materials*. 2017; 141:366–78. <https://doi.org/10.1016/j.conbuildmat.2017.02.117>
91. Eid R, Paultre P. Compressive behavior of FRP-confined reinforced concrete columns. *Engineering Structures*. 2017; 132:518–30. <https://doi.org/10.1016/j.engstruct.2016.11.052>.
92. Zhou Y, Liu X, Xing F, Cui H, Sui L. Axial compressive behavior of FRP-confined lightweight aggregate concrete: An experimental study and stress-strain relation model. *Construction and Building Materials*. 2016; 119:1–15. <https://doi.org/10.1016/j.conbuildmat.2016.02.180>.
93. Touhari M, Mitiche-Kettab R. Behaviour of FRP confined concrete cylinders: Experimental investigation and strength model. *Periodica Polytechnica Civil Engineering*. 2016; 60(4):647–60.
94. ASTM C494. "Standard specification for chemical admixtures for concrete." ASTM international, 1520/C0494_C0494M-10.
95. SABIC-Company. Product data sheet for Crystalline Polyethylene Terephthalate (PET)-BC210 [cited 2021]. Available from: <https://www.sabic.com/en/products/polymers/polyethylene-terephthalate-pet/sabic-pet?grade=bc210>.
96. Factory LP. Plastic Industries [cited 2021]. Available from: <http://www.lightplast.com/en/contact/>.
97. Product data sheet for SikaWrap - 300C [Internet]. Sika-Iraq. Available from: <https://irq.sika.com/content/dam/dms/iq01/g/sikawrap-300-c.pdf>.
98. Product data sheet for Sikadur-330 [Internet]. Sika-Iraq. Available from: <https://irq.sika.com/content/dam/dms/iq01/h/sikadur-330.pdf>.
99. ASTM D3039/D3039M. Standard test method for tensile properties of polymer matrix composites materials. West Conshohocken, Pennsylvania, United States: Annual Book of ASTM Standards; 2008.
100. COSQC. IQS No. 5: Portland cement. Baghdad, Iraq: Central Organization for Standardization and Quality Control; 1984.
101. COSQC. IQS No. 45: Aggregate from natural sources for concrete and building construction. Baghdad, Iraq: Central Organization for Standardization and Quality Control; 1984.
102. Sika-Iraq. Product data sheet for SikaWrap - 300C. SikaWrap®-300 C2017.
103. Sika-Iraq. Product data sheet for Sika ViscoCrete hi-tech 1316. In: admixture Hpswsr, editor. Erbil, Iraq 2016.
104. Dixon DE, Prestreza JR, Burg GR, Chairman SA, Abdun-Nur EA, Barton SG, et al. Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1–91). 1991:1–38.
105. ASTM C19 /C192M-15. Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. ASTM International: West Conshohocken, PA; 2015.
106. ASTM C617 / C617M-15. Standard Practice for Capping Cylindrical Concrete Specimens. ASTM International: West Conshohocken, PA; 2015.
107. ASTM-C39. Standard test method for compressive strength of cylindrical concrete specimens. West Conshohocken, PA: ASTM-International; 2015.
108. Mohammed AA. Flexural behavior and analysis of reinforced concrete beams made of recycled PET waste concrete. *Construction and Building Materials*. 2017; 155:593–604.
109. Sosoi G, Barbuta M, Serbanoiu AA, Babor D, Burlacu A. Wastes as aggregate substitution in polymer concrete. *Procedia Manufacturing*. 2018; 22:347–51.
110. Lam L, Teng JG. Design-oriented stress-strain model for FRP-confined concrete. *Construction and Building Materials*. 2003; 17(6–7):471–89.
111. Qaidi SMA. PET-concrete confinement with CFRP. 2021.
112. Qaidi SMA. PET-Concrete. 2021.
113. Park R, Paulay T. Reinforced concrete structures. New Zealand: John Wiley & Sons; 1975.
114. Richart FE, Brandtzaeg A, Brown RL. Failure of plain and spirally reinforced concrete in compression. Univ. of Illinois: Engineering Experimental Station, Urbana, Ill; 1929.
115. Richart FE, Brandtzaeg A, Brown RL. A study of the failure of concrete under combined compressive stresses. Univ. of Illinois: Engineering Experimental Station, Champaign, Ill; 1928.
116. Cusson D, Paultre P. Stress-strain model for confined high-strength concrete. *Journal of Structural Engineering*. 1995; 121(3):468–77.

117. Mohamed HM, Masmoudi R. Axial Load Capacity of Concrete-Filled FRP Tube Columns: Experimental versus Theoretical Predictions. *Journal of Composites for Construction*. 2010; 14(2):231–43. [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000066](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000066)
118. Samaan M, Mirmiran A, Shahawy M. Model of concrete confined by fiber composites. *Journal of Structural Engineering*. 1998; 124(9):1025–31.
119. Newman K, Newman J, editors. *Failure theories and design criteria for plain concrete* 1971; London, Great Britain: Concrete Materials Research Group, Imperial College.
120. Fafitis A, Shah SP. Predictions of ultimate behavior of confined columns subjected to large deformations. *Journal of the American Concrete Institute*. 1985; 82(4):423–33.
121. Saatcioglu M, Razvi SR. Strength and ductility of confined concrete. *Journal of Structural engineering*. 1992; 118(6):1590–607.
122. Eurocode 2. Design of concrete structures, part 1: General rules and rules for buildings. CEN, Bruxelles: Commission of European Communities ENV, CEN, Bruxelles; 1992.
123. Miyauchi K, Inoue S, Kuroda T, Kobayashi A. Strengthening effects of concrete column with carbon fiber sheet. *Transactions of the Japan Concrete Institute*. 1999; 21:143–50.
124. Fam AZ, Rizkalla SH. Confinement model for axially loaded concrete confined by circular fiber-reinforced polymer tubes. *ACI Structural Journal*. 2001; 98(4):451–61.
125. Fib Bulletin TG. Externally bonded FRP reinforcement for RC structures. Switzerland: International Federation for Structural Concrete 2001.
126. ISIS Canada Guidelines. Design manual no. 4: Strengthening reinforced concrete structures with externally bonded fiber reinforced polymers: Intelligent Sensing for Innovative Structures (ISIS) Winnipeg, Canada; 2001.
127. ACI 440.2R. Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures: Farmington Hills, MI: American Concrete Institute; 2002.
128. Ilki A, Kumbasar N, Koc V, editors. *Strength and deformability of low strength concrete confined by carbon fiber composite sheets*. 15th ASCE Engineering Mechanics Conference; 2002: Columbia University, New York, NY.
129. CNR-DT 200. Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures. Rome (Italy): Italian Council of Research (CNR); 2004.
130. Xiao QG, Teng JG, Yu T. Behavior and Modeling of Confined High-Strength Concrete. *Journal of Composites for Construction*. 2010; 14(3):249–59. [https://doi.org/10.1061/\(asce\)cc.1943-5614.0000070](https://doi.org/10.1061/(asce)cc.1943-5614.0000070) WOS:000277746800001.
131. Afifi MZ, Mohamed HM, Chaallal O, Benmokrane B. Confinement Model for Concrete Columns Internally Confined with Carbon FRP Spirals and Hoops. *Journal of Structural Engineering*. 2015; 141(9):04014219. [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0001197](https://doi.org/10.1061/(ASCE)ST.1943-541X.0001197)
132. Kwan AKH, Dong CX, Ho JCM. Axial and lateral stress–strain model for FRP confined concrete. *Engineering Structures*. 2015; 99:285–95. <https://doi.org/10.1016/j.engstruct.2015.04.046>.
133. Ahmed SK. Ultimate strength and axial strain of FRP strengthened circular concrete columns. *Cogent Engineering*. 2018; 5(1):1501971.
134. Raza A, Khan QuZ, Ahmad A. Prediction of axial compressive strength for FRP-confined concrete compression members. *KSCE Journal of Civil Engineering*. 2020; 24:2099–109.
135. Hussain Q, Ruangrassamee A, Tangtermsirikul S, Joyklad P. Behavior of concrete confined with epoxy bonded fiber ropes under axial load. *Construction and Building Materials*. 2020; 263:120093.